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Paleogene paleoceanography : Early Cenozoic oceans revisited

Paleogene
Paleocirculation
Paleoclimate
Paleobiogeography

Paléogène
Paléocirculation
Paléoclimat
Paléobiogéographie

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ABSTRACT

This paper is a review of the emerging unified view of the history of ocean circulation and climates during the Paleogene (65-24 Ma) based on evidence from many disciplines. Major threshold events at the Cretaceous/Tertiary boundary (65 Ma), in the latest Paleocene-early Eocene (53-49 Ma) and near the Eocene/Oligocene boundary (38 Ma), that profoundly effected the oceanographic/climatic history of the world ocean, are reviewed with special emphasis. Inferred global surface circulation maps are presented on paleogeographic reconstructions of the early Paleocene, middle Eocene and late Oligocene intervals.
The Paleogene was characterized by cooling high latitude temperatures and the development of greater latitudinal thermal contrast that eventually led to the predominantly glacial mode of the Neogene. According to one model, during the Paleogene, the mode of deep water formation changed from predominantly in the low and mid latitudinal marginal seas, producing warm, saline, bottom water, that was characteristic of the late Cretaceous, to predominantly in the high latitudinal areas, producing cold, dense, bottom water, characteristic of the present time.
Paleogene planktonic biogeographic data (shifts of assemblages through latitudes) and oxygen-isotopic data show cooling events in middle Paleocene, middle Eocene and near the Eocene/Oligocene boundary, and a major warming event that culminated in peak warming during the early Eocene. Biogeographic data show additional cooling events in the earliest Paleocene and middle Oligocene, and a warming event in the later middle Eocene. Plankton migrations data indicate that the middle Oligocene cooling episode may have been as severe as that near the Eocene/Oligocene boundary.

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RÉSUMÉ

Paléo-océanographie paléogène : synthèse sur les océans du Cénozoïque inférieur.

Cet article présente une revue des idées générales émises à propos de la circulation océanique et des climats au cours du Paléogène (65-24 Ma), basées sur des informations provenant de différentes disciplines. On met l'accent sur les événements qui ont profondément affecté l'histoire océanographique et climatique de l'océan mondial à la limite Crétacé-Tertiaire (65 Ma), au Paléocène inférieur-Éocène inférieur (53-49 Ma) et vers la limite Éocène-Oligocène (38 Ma). On présente des cartes de la circulation générale de surface reportée sur des reconstructions paléogéographiques des époques Paléocène inférieur, Éocène moyen et Oligocène supérieur.
Le Paléogène est caractérisé par un refroidissement dans les zones de hautes latitudes et le développement d'un plus grand contraste thermique latitudinal, qui a éventuellement conduit au mode glaciaire prédominant au Néogène. D'après un modèle, le mode de formation de l'eau profonde durant le Paléogène est passé d'une production d'eau profonde chaude et saline dans les mers marginales de basse et moyenne latitude, qui a caractérisé le Crétacé supérieur, à une production d'eau profonde froide et dense dans les zones de hautes latitudes, caractéristique de l'époque actuelle.
Les données biogéographiques sur le plancton du Paléogène (changements d'assemblages

suivant la latitude) et celles sur les isotopes de l'oxygène montrent des épisodes de refroidissement au Paléocène moyen, à l'Éocène moyen et près de la limite Éocène-Oligocène, ainsi qu'un épisode majeur de réchauffement, qui a atteint son maximum au cours de l'Éocène inférieur. Les données biogéographiques montrent des épisodes de refroidissement supplémentaires au Paléocène basal et à l'Oligocène moyen, ainsi qu'un épisode de réchauffement à la partie supérieure de l'Éocène moyen. Les données sur les migrations planctoniques indiquent que l'épisode de refroidissement de l'Oligocène moyen a pu être aussi brutal que celui de la limite Éocène-Oligocène.

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INTRODUCTION

In the history of the oceans, the Paleogene interval (65 to 24 Ma) is perceived as an intermediate phase, characterized by changing thermal patterns in the world ocean and a transition from a predominantly thermospheric circulation to predominantly thermohaline circulation, as well as from a non-glacial to a glacial mode. The Cretaceous oceans were characterized by high sea levels, warm high latitude temperatures, low thermal gradients and generally equable climates. A major threshold was crossed during the early Tertiary when higher latitudes gradually began to cool, developing steeper latitudinal thermal gradients and accentuating seasonality, that eventually culminated in the predominantly glacial Neogene and the atmospheric-hydrographic patterns of today.

In the past decade evidence from a number of independent avenues of research is converging to provide a unified view of of the paleoceanography and paleoclimatology of the Mesozoic and Cenozoic times. It has become evident that both long and short term events have influenced the global paleoceanographic patterns. Long term events, such as those related to the vertical and horizontal crustal movements and changes in the rates of spreading at ridge axes, and relatively short term events, such as opening and closing of marine passageways, have profoundly effected the global hydrographic and atmospheric patterns, which in turn influenced the evolution and distribution of organisms in the biosphere.

This paper reviews the Paleogene oceanographic/climatic history of the world ocean, with special emphasis on the major events at the Cretaceous/Tertiary boundary, in the latest Paleocene-early Eocene and near the Eocene/Oligocene boundary. Earlier reviews of the Mesozoic-Cenozoic paleoceanographic history of the world ocean include : Berggren and Hollister (1974 ; 1977), Berger (1979), Arthur (1979), van Andel (1979) and Schnitker (1980). Regional syntheses can also be found in special volumes and papers : Atlantic Ocean (Talwani *et al.*, 1979), South Atlantic (McCoy, Zimmerman, 1977), Indian Ocean (McGowran, 1978 ; Kidd, Davies, 1978 ; see also Heirtzler *et al.*, 1977 ; von der Borch, 1978), Pacific Ocean (van Andel *et al.*, 1975) and Southern Ocean (Kennett, 1977 ; 1978). To develop a background for the discussion of major threshold events, the general review of the oceanographic-climatic conditions of the Paleogene is presented first in the section below. This is followed by an extended discussion of the biotic crisis at the Cretaceous/Tertiary boundary, the climatic optimum in the early Eocene, and the climatic deterioration and formation of the psychrosphere near the Eocene/Oligocene boundary.

TRANSITION FROM THERMOSPHERIC TO THERMOHALINE CIRCULATION : OCEANOGRAPHIC TRENDS IN THE PALEOGENE

The late Cretaceous ocean was characterized by mild climates and a lack of significant temperature contrast between high and low latitudes (Douglas, Savin, 1975), indicating that the surface and deep water circulation was probably sluggish. Modular circulation experiments have shown the existence of two surface cyclonic gyres in the Pacific and a prominant clockwise gyre in the widening North Atlantic (Luyendyk *et al.*, 1972). The late Cretaceous deep water temperatures were relatively warm as well (Savin, 1977), a condition fundamentally different than the cold bottom water regime that developed in the mid Tertiary.

Recently Brass *et al.* (1980) have suggested that during the Cretaceous bottom water may have been produced by the sinking of warm, salty, water formed by evaporation in low and mid latitude marginal seas, rather than by sinking of cold, dense, water formed in higher latitude marginal seas as at present time. During the late Cretaceous the area of epicontinental seas within the zone of net evaporation (10-40°N and S latitudes) was relatively large, and Brass *et al. (op. cit.)* propose that this led to the production of warm, high salinity, waters by evaporation over the marginal seas, that sank to form the warm, saline bottom water (WSBW), characteristic of this interval. These authors also maintain that since the solubility of CO_2 in water decreases with increasing temperature, during times when WSBW production was large, atmospheric CO_2 levels may have been large as well, and this would have led to increased poleward latent heat transport, decreasing the latitudinal thermal contrast.

Brass *et al.* (1980) go on to suggest that area of shallow seas within the net evaporation zone of low and mid latitudes has decreased through the Cenozoic, particularly near the Eocene/Oligocene boundary, caused by a wide regression that may have forced the transition to the mode of deep water formation to the higher latitudes. This model implies that changes in the areas of marginal seas caused by tectonic and eustatic fluctuations are ultimately responsible for the mode of deep water formation and circulation, and forcing mechanism for climatic change.

The Paleocene world ocean (Fig. 1) continued to be dominated by the circulation patterns established during the Cretaceous. The paleo-Gulf Stream that developed in the Cretaceous, continued to flow towards the margins of the southern Labrador Sea which had begun opening by Campanian/Maestrichtian time (Gradstein, Srivastava, 1980). The Tethys Current, which dominated the tropical

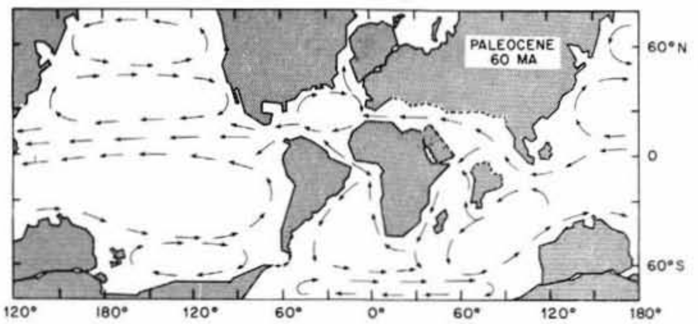


Figure 1
Inferred global surface circulation patterns during the early Paleocene plotted on paleogeographic reconstruction of Smith and Briden (1977), with modifications for certain regions based on more detailed studies and reconstructions by Molnar et al. *(1975), Sclater* et al. *(1977), Talwani and Eldholm (1977), and Gradstein and Srivastava (1980). Clockwise subpolar gyres in the southern Atlantic and Pacific Oceans are inferred to have existed in the absence of a circum-Antarctic Current system.*

circulation, flowed westward through the Tethys Seaway and the Panama Straits to form a circum-global tropical current, contributing to the widespread dispersal of marine biota from Jurassic to mid Tertiary (Hallam, 1969, Berggren, Hollister, 1974). An anti-clockwise subpolar surface gyre had probably existed in the South Atlantic prior to early Paleocene (Ciesielski, Wise, 1977) and an eastward flowing current hugged the edge of Antarctica and northern Australia. Clockwise flowing cells to the south of the northward drifting Indian plate were the major features of the Indian Ocean. The Tethys Current continued into the Pacific as an equatorial current, and experimental circulation studies (Luyendyk *et al.*, 1972) indicate two northern Hemisphere gyres with return flow in the high latitudes (van Andel, 1979). In the absence of the circum-Antarctic Current, anti-clockwise gyres must have existed in the southern Pacific and Atlantic Oceans (see Fig. 1).

The Paleogene tectonic considerations suggest a reduction of the northern area in the Pacific and the resulting increase in the pole to pole asymmetry probably led to enhanced importance of the southern high latitudes as the source area for deep waters (Schnitker, 1980). At this time southern high latitudes assumed an increased role in deep water circulation for Indian and Atlantic Oceans as well, and a concomitent decrease in the shallow marginal seas within the low and mid latitude net evaporation zone (Brass *et al.*, 1980), set the stage for a change in the mode of bottom water formation in the lower latitudes in Cretaceous to higher latitudes in the later Tertiary.

The major paleogeographic events that influenced the circulation and sedimentation patterns in the Paleogene world ocean are listed in the Table along with the geophysical and paleontological sources for these events. It must be emphasized, however, that the timing of a number of these events, based mainly on magnetic anomaly patterns, are approximate at best. One of the main problems at the present time is assessing cause and effect relationships based on approximate dating.

Numerous important paleogeographic events occurred during the Paleocene. In the Atlantic, the separation of Greenland and Scandinavia and the formation of the embryonic Greenland and Norwegian Seas had begun in the early Paleocene between 60 and 58 Ma (Pitman, Talwani, 1972 ; Talwani, Eldholm, 1977) (see also Tucholke, Vogt, 1979 and Eldholm, Thiede, 1980, for summaries of the tectonic history of North Atlantic).

During the Paleocene the southern Labrador Passage conti-

Table
Major paleogeographic events in the Paleogene that influenced the paleoceanographic history of the world ocean.

AGE	PALEOGEOGRAPHIC EVENTS	REFERENCES
1. Early Paleocene (60-58 Ma)	Separation of Greenland and Scandinavia and the formation of Greenland and Norwegian Seas begins	Pitman and Talwani, 1972 ; Talwani and Eldholm, 1977
2. Late Paleocene (55-53 Ma)	Australia and Antarctica separate and Australia commences drifting northwards. Formation of the ocean between the two continents begins	Weissel and Hayes, 1972 ; Kennett, 1977
3. Early Eocene (Ca. 53 Ma)	Open Norwegian-Greenland Sea develops surface water exchange with the Arctic Ocean	Talwani and Eldholm, 1977 ; Thiede, 1979
4. Late Eocene (Ca. 40 Ma)	Subsidence of South Tasman Rise permits shallow connection between Indian and Pacific Oceans	Kennett *et al.*, 1975 ; Kennett, 1977
5. Late Eocene (40-37 Ma)	Tethys partially restricted north and east of Indian Plate	Veevers *et al.*, 1971
6. Late Eocene (Ca. 38 Ma)	Iceland-Faeroe sill sinks below sea level for the first time	Talwani *et al.*, 1976
7. Eocene/Oligocene Boundary (39-37 Ma)	Completion of the opening of Labrador Sea which had begun in the Maestrichtian	Laughton, 1971 Gradstein and Srivastava, 1980
8. Early Oligocene (38-35 Ma)	Shallow connection between South Pacific and Atlantic developed at Drake Passage	Sclater (pers. comm., 1980)
9. Early Oligocene (37-35 Ma)	Separation of Greenland and Svalbard and availability of higher latitude water to North Atlantic	Talwani and Eldholm, 1977
10. Early Oligocene (Ca. 35-33 Ma)	Tethys severely restricted in the eastern part due to uplift of the Himalayas	Laughton *et al.*, 1973 ; Berggren and Hollister, 1974
11. Middle Oligocene (33-30 Ma)	Isolation of Antarctica completed after further subsidence of South Tasman Rise	Kennett, 1977

nued to widen, and the northern Labrador also began opening (Laughton, 1971 ; Gradstein, Srivastava, 1980). There are some indications that the Greenland-Faeroe Ridge may have begun sinking in the earliest Eocene (Laughton, 1971). By early Eocene (ca. 53 Ma) the newly opened Norwegian-Greenland Sea had developed surface water exchange with the Arctic Ocean (Talwani, Eldholm, 1977 ; Thiede, 1980).

In the Indian Ocean there is indication that India may have arrived at a subduction zone in the Tethys Sea to the north sometime in the latest Paleocene-early Eocene (Laughton *et al.*, 1973 ; Curray, Moore, 1974). This did not severely restrict the Tethys Current which continued to flow westward through the northern passage and the triangular reentrant west of the Indian plate until the end of early Eocene, during which time the northern passage was further restricted, shifting the main flow to the west of the Indian plate. Tethys Current continued to flow through this western passage until late Eocene. This is evidenced by the presence of extensive neritic and marginal marine deposits of middle to late Eocene age in Pakistan (McGowran, 1978). In the Oligocene this flow became sharply reduced and intermittent, and may have become restricted to a narrow southwestern passage.

In the Southern Ocean there is geophysical and paleontological evidence of the separation of Australia and Antarctica and the formation of ocean between the two continents in the late Paleocene (ca. 53 Ma) (Weissel, Hayes, 1972 ; Kennett, 1977). The event is apparent from the erosional hiatuses of this age in the Tasman Sea area (Kennett *et al.*, 1975). The initial subsidence of the South Tasman Rise in the late Eocene allowed a shallow connection between the Indian and Pacific Oceans and set the stage for the ultimate development of the circum-Antarctic circulation in the mid Cenozoic.

The Greenland-Iceland-Faeroe Ridge system forms a dominant topographic high that blocked the exchange of waters between the Norwegian-Greenland Sea and the North Atlantic (Vogt, 1972). The subsidence history of this ridge is therefore crucial to the understanding of the paleoceanography of the region. According to Ewing and Hollister (1972) the ridge may have subsided enough by the late Eocene to permit at least some inflow of colder, dense, water into the North Atlantic and the initiation of North Atlantic Deep Water (NADW). Recently two sites (336 and 352) were drilled in this area during Leg 38 of the Deep Sea Drilling Project (DSDP) and results suggest that Site 336 subsided below sea level during late Eocene and early Oligocene (Talwani *et al.*, 1976). This subsidence, however, led only to a partial submergence of the ridge, not sufficient for a significant outflow of NADW. The main ridge plateform did not submerge before the middle Miocene (Eldholm, Thiede, 1980) which would have led to a substantial flow of NADW into the North Atlantic.

The inferred surface paleocirculation patterns during the middle Eocene are shown in Figure 2. The patterns are essentially similar to those in the early Paleocene (cf. Fig. 1), with the exception of a more restricted Tethyian flow from the Indian Ocean towards the Atlantic and the presence of a passage between Australia and Antarctica that would have permitted at least a restricted surface water flow through the passage. By this time the Labrador Passage was a host to active transference of relatively warm North Atlantic waters into the Arctic (Gradstein, Srivastava, 1980). The Labrador Basin essentially attained its present size in the latest Eocene.

In the late Eocene (ca. 40 Ma) the subsidence of the South Tasman Rise finally allowed a free surface connection between the Indian and Pacific Oceans (Kennett *et al.*, 1975), which enhanced the development of the circum-Antarctic Current, and the isolation of Antarctica (with the exception of a still closed Drake Passage) was significant enough to lead to the first large scale freezing at sea level (Kennett, 1977) and the initiation of Antarctic Bottom Water (AABW) near the Eocene/Oligocene boundary (ca. 38 Ma). This is evidenced by the widespread scouring of bottom sediments and the occurrence of erosional hiatuses in the East Indian and Soutwest Pacific Oceans in the early Oligocene, caused by the accelerated activity of the bottom currents (Moore *et al.*, 1978). This was also a major threshold event that led to the formation of the psychrosphere (cold bottom layer of a two-layered ocean, characterized by a psychrospheric fauna, Benson, 1975 ; Kennett, Shackleton, 1976) and the development of a thermohaline circulation (Kennett, 1977). Addition of younger, more oxygenated, water (with relatively lower concentration of CO_2 and therefore lower acidity) to the bottom water regime resulted in marked drop in the calcite compensation depth (CCD) at this time (Berger, 1973).

One of the most important Paleogene paleogeographic events was the opening of the Drake Passage that effected development of the circum-Antarctic Current and the complete thermal isolation of Antarctica. The date of this crucial event has been a matter of debate because the magnetic anomalies on both sides of the Passage are complex and poorly understood. The most commonly quoted date for the establishment of a connection between South Pacific and Atlantic is late Oligocene, around 30 Ma (Barker, Burrell, 1977 ; Kennett, 1977). However, more recent attempts at plate reconstructions indicate that at least a shallow connection existed at the Drake Passage as early as the early Oligocene, between 38 and 35 Ma (Sclater, pers.

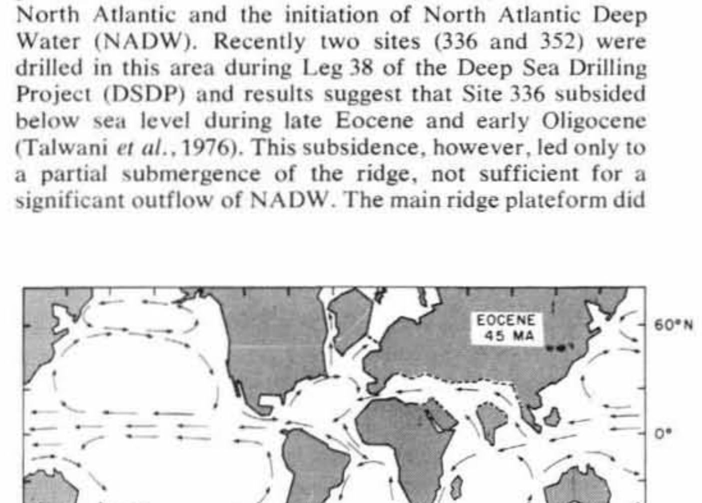


Figure 2

Inferred global surface circulation patterns during the middle Eocene (see caption of Fig. 1 for data used for the paleogeographic base-map). The Tethys Current north of the Indian Plate may have been more restricted than shown, major entrance for the current being west of the Indian Plate. Clockwise southern Atlantic and Pacific Ocean gyres are still prominant due to the disrupted flow of circulation around Antarctica because of the still closed Drake Passage.

comm., 1980). The total thermal isolation of Antarctica was, on the other hand, not accomplished until mid Oligocene (33-30 Ma) when South Tasman Rise subsided further. The deeper connection at the Drake Passage probably did not develop until middle Miocene, at about 15 to 16 Ma (Sclater, pers. comm., 1980).

The early Oligocene (37-35 Ma) also saw the separation of Svalbard and Greenland (Talwani, Eldholm, 1977) and the availability of higher latitude source of colder water to the North Atlantic. During the early Oligocene the north eastern part of the Tethys was almost completely closed, which severely restricted the westward flow of the Tethys Current, limiting it to intermittent flow west of the Indian plate.

By the late Oligocene the global surface circulation patterns had essentially evolved the major present day features and looked substantially different from those of the Paleocene-Eocene interval (*cf.* Fig. 2 and 3). The most obvious changes were the development of the circum-Antarctic Current, the near-cessation of the eastern part of Tethys Current due to the initial uplift of the Himalayas, and the exchange of North Atlantic surface waters with the Arctic, both through the Norwegian-Greenland Sea and the Labrador Passage. Paleontological evidence indicates that there was a return flow from the Arctic into the North Atlantic via the Labrador Sea during the late Oligocene (Gradstein, Srivastava, 1980) following a global lowering of sea level in mid Oligocene (Vail *et al.*, 1977). Because of the evolution of circum-Antarctic Current, the smaller, clockwise, southern Hemisphere cyclonic gyres in both the South Pacific and Atlantic were severely restricted. Other major Oligocene circulation patterns were analogous to those inferred for the Eocene.

PALEOGENE PALEOCLIMATES : DECLINE IN GLOBAL TEMPERATURES

Cenozoic global climates have been characterized by the step-like transitions from one quasi-equilibrium state to another (Kennett, 1978 ; Berger, 1979). The Cenozoic climates as a whole show a marked decline in global temperatures at higher latitudes, as indicated by the progressive increase in $\delta^{18}O$ values of benthic foraminifera (see Fig. 4) (Shackleton, Kennett, 1975 ; Savin, 1977).

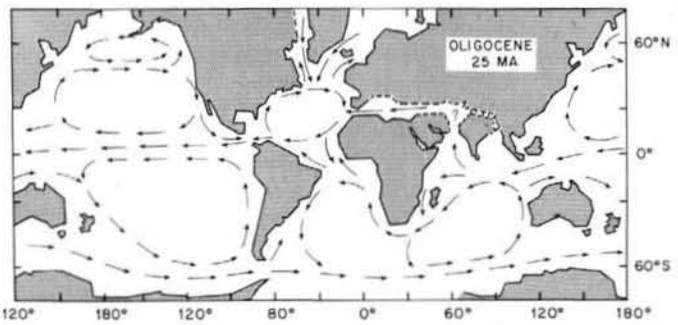


Figure 3

Inferred global surface circulation patterns during the late Oligocene (see caption of Fig. 1 for the data used for paleogeographic base-map). The Tethys Current is now severely restricted at its eastern entrance and intermittent flow may be limited to a narrow passage between Indian and Arabian Plates. The clockwise subpolar gyres in the southern oceans may have severely restricted at this time due to the development of the circum-Antarctic Current after the surface connection at the Drake Passage in early Oligocene.

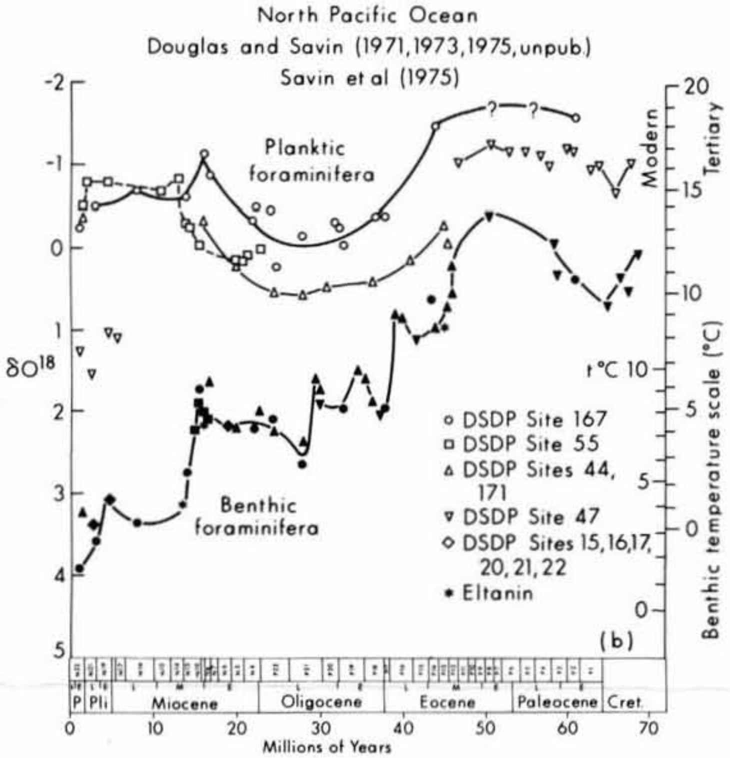


Figure 4

Cenozoic planktonic and benthic foraminiferal oxygen-isotopic data summarized from various DSDP Sites (after Savin, 1977). Planktonic foraminiferal $\delta^{18}O$ yields information about surface temperatures prevailing during the lifetime of the species, and benthic foraminifera about bottom temperatures. Deep water temperatures are also indicative of surface water temperatures that prevailed at higher latitudes where cool, dense, water sinks to form bottom water — a comparison of planktonic and benthic isotopic temperatures thus yields information about past latitudinal thermal gradients. Notice the sharp decline in benthic temperatures, indicating that the Cenozoic cooling is mainly a high latitude phenomena (for references in the figure, see Savin, 1977 ; figure courtesy S. M. Savin).

Both the paleontological and the oxygen-isotopic record are relevant to the delineation of Paleogene climates. The paleontological record is essentially in the form of planktonic paleobiogeographic patterns, which reveal numerous poleward extensions of tropical assemblages, and equatorward extensions of cold, higher latitude, assemblages during certain time intervals (Haq, Lohmann, 1976 ; Haq *et al.*, 1977).

Paleobiogeographic Record

Figure 5 illustrates the major calcareous planktonic (nannofossil and planktonic foraminiferal) migrationary patterns during the early Cenozoic in the North Atlantic Ocean (Haq *et al.*, 1977). Migrations towards higher latitudes are interpreted as being caused by climatic warming and towards lower latitudes by climatic cooling. These events indicate a relatively cool earliest Paleocene (65-63 Ma), followed by a warming between 63 and 60 Ma. An important cooling event occurred in the middle Paleocene (60-57 Ma) when both high latitude nannofloral and planktonic foraminiferal assemblages show a marked shift into the lower latitudes. The event is followed by a marked warming in the late Paleocene-early Eocene (53-49 Ma), indicated by the shift of low latitude assemblages into high latitudes, as far north as 50-55°N.

The late Paleocene warming trend culminated in period of peak warming during the early Eocene, probably the warmest interval of the Cenozoic (Haq *et al.*, 1977). Data from terrestrial flora and fauna corroborate this peak warming and also suggest that the warm, tropical/subtropical belt expanded to double its present latitudinal extent. Tropical flora on the west coast of North America extended as far north as 45°N latitude and temperate floras up to 60°N in the Gulf of Alaska in the early Eocene (Wolfe, 1978). The Ellesmere Island, north of Baffin Bay in the Canadian Arctic, has yielded a rich early Eocene vertebrate fauna, adapted to warm conditions, indicating minimum temperatures of 10-12°C during winters (Estes, Hutchison, 1980 ; McKenna, 1980).

Marine assemblage migrations in the North Atlantic (see Fig. 5) suggest a middle Eocene (46-44 Ma) cooling, when higher latitude assemblages show another incursion into lower latitudes. This is followed by a general climatic amelioration, until a second important incursion of higher latitude assemblages into lower latitudes near the Eocene/Oligocene boundary (38-36 Ma). A third invasion of higher latitude assemblages into lower latitudes occurred in the mid Oligocene, indicating another cooling episode between 32 and 30 Ma. This cooling event was apparently equal in intensity to the latest Eocene-early Oligocene event of marked climatic deterioration (Haq *et al.*, 1977).

Oxygen-isotopic Record

The oxygen-isotopic paleoclimatic data from various parts of the ocean agrees remarkably well with the paleoclimatic conclusions based on Paleogene calcareous planktonic temporal and spatial shifts. In Figure 6 the Paleogene oxygen isotope data from various sources has been summarized. The curves from North Atlantic DSDP Site 398 (Vergnaud-Grazzini *et al.*, 1978) and North Sea (Buchardt, 1978) show a relatively cooler early Paleocene (lower $\delta^{18}O$ values). Boersma and Shackleton (1977) and Boersma *et al.* (1979) have documented a decrease in the benthic isotopic temperature in the mid Paleocene at the South Atlantic DSDP Site 357, and the western North Atlantic Site 384. At the latter site the planktonic foraminiferal data also show low isotopic temperatures between 61 and 60 Ma.

The latest Paleocene-early Eocene climatic amelioration has been documented in numerous oxygen-isotopic studies and is obvious in all the curves reproduced in Figure 6. Both the benthic and planktonic foraminiferal data show a decrease in $\delta^{18}O$ values. Shackleton and Kennett (1975) recorded high isotopic temperatures based both of planktonic and benthic species in the southern high latitude Site 277. Buchardt's (1978) molluscan oxygen-isotopic curve show a sharp rise in paleotemperatures of shallow marginal seas in NW Europe during late Paleocene-early Eocene interval. Similar trends

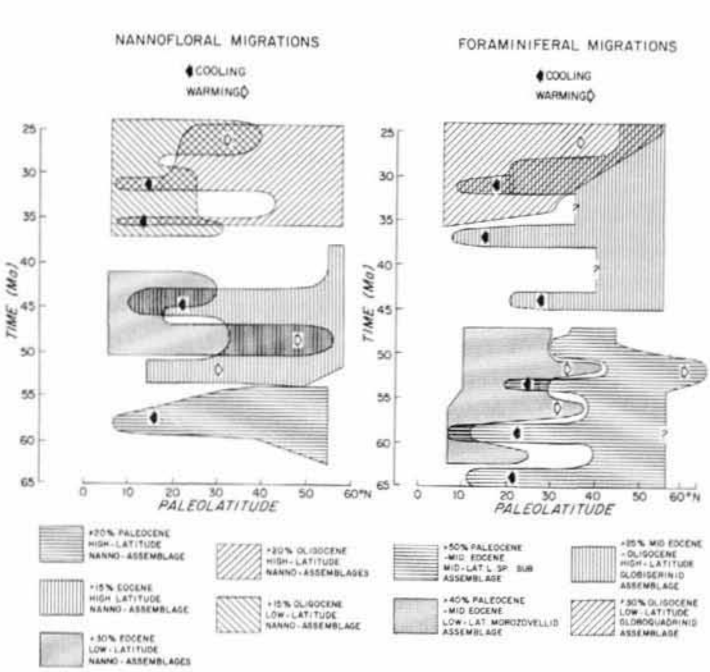
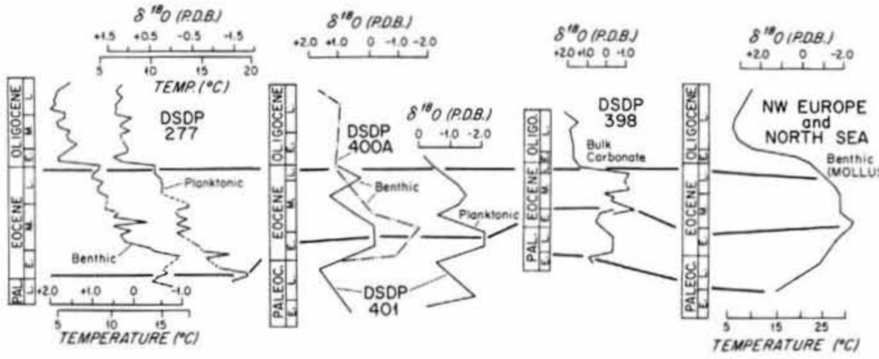


Figure 5

A summary of nannofloral and planktonic foraminiferal migrations through latitudes interpreted as a response to major climatic fluctuations during the Paleogene in the North Atlantic Ocean. The shifts of low-latitude assemblages to higher latitudes (white arrows) indicate warmings, and shifts of high-latitude assemblages to lower latitudes (black arrows) indicate cooling events. These patterns help in the interpretation of the climatic history (relative cooling and warming episodes) of the Atlantic Paleogene (after Haq et al., *1977).*

Figure 6

Paleogene oxygen-isotopic paleotemperature data from various sources. Planktonic and benthic δ¹⁸O data from Site 277 (Campbell Plateau, Southwest Pacific Ocean) after Shackleton and Kennett (1975) ; data from Sites 400, 401 and 398 (North Atlantic Ocean) after Vergnaud-Grazzini et al. *(1978), and molluscan data from NW Europe and the North Sea after Buchardt (1978). Major climatic events (in middle Paleocene, early Eocene and at the Eocene/Oligocene boundary) are marked by connecting horizontal lines.*



have also been recorded from sequences at Sites 398 and 401 in the North Atlantic by Vergnaud-Grazzini *et al.* (1978) in both the benthic and planktonic Foraminifera.

After the early Eocene peak warming, the isotopic curves show a long term cooling trend that culminated in a sharp decrease in both the planktonic and benthic isotopic paleotemperatures near the Eocene/Oligocene boundary. The middle Eocene cooling indicated by assemblage migrationary patterns (see Fig. 5) is also evident from the oxygen-isotopic data from Site 277 (Shackleton, Kennett, 1975) and at Site 357 (Boersma, Shackleton, 1977).

The late Eocene-early Oligocene cooling event has been well documented in the oxygen-isotopic record. At Site 277 a sharp drop in surface and bottom temperatures in evident (Shackleton, Kennett, 1975) ; at North Atlantic Sites 398 and 401 a marked cooling trend has been recorded (Vergnaud-Grazzini *et al.*, 1978), and the NW European data show a similar precipitous drop at the Eocene/Oligocene boundary (Buchardt, 1978). This sharp cooling near the Eocene/Oligocene boundary is one of the step-like transitions, characteristic of Cenozoic global climates (see discussion under "terminal Eocene event"). The mid Oligocene cooling event is not obvious in the isotopic record which shows relatively low amplitude variations during most of the Oligocene.

THE CATASTROPHIC EVENT AT THE CRETACEOUS/TERTIARY BOUNDARY

The Cretaceous/Tertiary (K/T) boundary is conveniently placed near one of the most dramatic events in Earth history, marked by the depletion of a large percentage of world's biota in a relatively short time. Less than 25 % of late Cretaceous species survived into the Tertiary. In the ocean the revolutionary aspect of this event is evident from the widespread presence of clays and hard-grounds at the boundary. The land-based marine sections most often show a marked hiatus at the boundary. The Cenozoic thus began with what was an event of relatively short duration (on the order of 10,000 years ; Kent, 1978), but of catastrophic proportions. Among the marine groups most effected by this event were the phyto- and zooplankton, the ammonites and belemnites, the shallow-dwelling echinoderms, corals, many bivalve groups, large benthic foraminifera and the large marine reptiles. On land, the dinosaurs and the flying reptiles were the most celebrated casualties (although there is still some doubt as to the synchroniety of the plankton and reptilian extinctions). Recent paleobotanical work suggests that there was an abrupt change in the terrestrial floras across the K/T boundary as well (Krassilov *vide* Hallam, 1979). Deep water benthics and fresh water faunas remained relatively unaffected by this otherwise all-embracing event.

In recent years there has been a great revival of interest in the terminal Cretaceous event. Speculations about the reasons for this revolutionary event abound, and invoke both terrestrial and extra-terrestrial causes. Sharp changes in climate, depletion of nutrients, poisoning of the water and atmosphere, physical catastrophes, magnetic reversals, cosmic and supernovae radiation, and impact of meteorites, asteroids and comets have all been proposed as possible causes (see Beland *et al.*, 1977, and Russell, 1977, for recent reviews on the subject of K/T boundary event).

Recent discovery of enrichment over the background levels of Iridium and other noble elements in the sediment layers at the K/T boundary in sections from Italy, New Zealand and Denmark (Alvarez *et al.*, 1980 ; Ganapathy, 1980) and Spain (Smit, Hertogen, 1980) lend credence to an extra-terrestrial cause of this catastrophic event. The isotopic composition of Iridium in the boundary clays suggests an extra-terrestrial source within the solar system (Alvarez *et al.*, 1979) and a meteoritic or asteroidal impact, rather than a supernova, is now favored by the proponents of the extra-terrestrial causes. The scenario proposes a post-impact distribution of pulverized rock in the atmosphere over the entire globe for several years, resulting in both the heating-up and darkening of the atmosphere. The suppression of photosynthesis would have an immediate detrimental effect on biota. Emiliani (1980) suggested that such an impact of a large Apollo object would introduce an exceptionally large amount of energy in a short time which, if trapped as heat energy, would have raised the temperature of the upper 50 m of the oceans and the lower troposphere by some 5-10°C. Such an increase would be lethal to flora and fauna in the lower latitudes, and Emiliani believes this to be the reason for the extinctions to have been relatively less severe in the higher latitudes and deeper waters.

A variation on the theme of the extra-terrestrial cause has been suggested by Hsü (1980), who maintains that the land animals were killed by the atmospheric heating during a cometary impact, and the marine calcareous plankton extinctions followed as a consequence of poisoning by cyanide released from the comet and the rise of the CCD in the oceans after detoxification of the cyanide. Hsü believes that the systematic search for the impact crater should be concentrated in the ocean, which would be the most likely place for such a feature (since the oceans cover a 73 % area of the globe), assuming that it has not already disappeared by subduction.

Among the terrestrial causes for the K/T boundary biospheric revolution, the most intriguing recent suggestion has been the Arctic "spill-over" (Gartner, Keany, 1978) or the "injection event" (Thierstein, Berger, 1978). This model requires the isolation of the Arctic Ocean in the latest Cretaceous, which would have turned this basin into a body of fresh or brackish water, that subsequently reconnected to the North Atlantic 65 millions years ago, at the time of the initial rifting between Greenland and Norway. Intrusion of saline waters from the North Atlantic would have flushed the lighter Arctic water which would have spilled over into the North and South Atlantic and rapidly covered the entire world ocean with a layer of cooler, low salinity, water. This injection of lower-salinity water would have an immediate detrimental effect on the open-ocean plankton, but the deeper living species would remain relatively uneffected. Gartner and McGuirk (1979) argue that this event would be followed by rapid and marked changes in global climates, by lowering the temperature and precipitation, triggering a series of ecologic disasters that would radically change the distribution patterns of vegetation on the earth and lead to the extinction of dinosaurs and other land animals.

Two different lines of evidence were brought to bear upon the Arctic spill-over model for the K/T boundary event. The "crucial" evidence presented by Gartner and Keany (1978) was the presence of thick nannofossil-bearing Maestrichtian sequences below and above a thin layer containing Danian nannofossils in a North Sea well. They argued the so-called Danian nannoplankton developed in an isolated Arctic during the late Maestrichtian and their presence within the (assumed) *in situ* Maestrichtian suggests a temporary intrusion of the Arctic waters into the North Sea, representing a drastic change in the normal marine conditions. Perch-Nielsen *et al.* (1979) and Watts *et al.* (1980), however, have taken issue with this interpretation, and show reason for reinterpreting the thick Maestrichtian sequence above the thin Danian layer as a reworked deposit of debris-flow origin (redeposited during late Danian), a phenomenon not uncommon in the North Sea sequences.

The second line of evidence, that Thierstein and Berger (1978) base their case upon, was the dramatic decrease in the oxygen and carbon isotopic values in the carbonate fine-fraction that they recorded across the K/T boundary in DSDP Site 356 on Sao Paolo Plateau in the South Atlantic. In more recent studies this shift in isotopic values doesnot seem to be apparent in the planktonic foraminifera (Boersma, Shackleton, 1979 ; Thierstein, pers. comm., 1980), and the argument for a fresh-water layer accounting for the decrease in oxygen isotopic values has been considerably weakened.

In addition to the above counter arguments, there also seems to be considerable doubt as to the probability of isolation and subsequent reconnection of the Arctic Ocean near the K/T boundary, which is a *causa sine qua non* of the Arctic spill-over model. Both Gartner and Keany (1978) and Thierstein and Berger (1978) consider the initial rifting between Greenland and Norway to have occurred at the K/T boundary and the passage thus produced to have been continuous and wide enough for the North Atlantic waters to intrude into the Arctic. The magnetic anomaly data, however, support a considerably younger age for the initial opening of this passage. Talwani and Eldholm's (1977) data clearly shows the oldest anomaly in the Norwegian-Greenland Sea to be anomaly 24 — there is no evidence of anomaly 25 in the region. This assigns the oldest possible age of 58 Ma (between anomalies 24 and 25), to the initial rifting, which could have produced a continuous open passage between the two oceans. In addition there is now evidence that suggests a narrow sea strait linking the North Atlantic with the Arctic through the Labrador Passage since the Campanian, with surface circulation towards the Arctic (Gradstein, Srivastava, 1980).

In spite of the diversity of explanations offered for the terminal Cretaceous catastrophe, none seems to satisfy all the available facts, and the controversy is likely to continue in the future. However, the scenarios suggested by each model, whether it be masking of sunlight and supression of photosynthesis, or the temporary poisoning of the oceans, or the rapid lowering of salinity of the surface waters, all have the potential of producing a marked destablizing effect on the oceanic plankton, and through them on the CO_2 cycle, the climate and ultimately the terrestrial flora and fauna as well.

THE EARLY EOCENE CLIMATIC OPTIMUM

As mentioned earlier, the late Paleocene global warming trend culminated in the early Eocene in the warmest interval of the entire Cenozoic. This period (53-49 Ma) seems to have been the best possible scenario for the optimal spread and growth of temperate marine biota. A wide-spread transgression (Vail *et al.*, 1977) apparently enlarged the ecospace for marine organisms. Increased productivity led to high carbonate (and total sediment) accumulation rates (Davies *et al.*, 1977) in the later part of early Eocene and early middle Eocene (Fig. 7). The oceanic sections show the lowest occurrence of hiatuses in the early Eocene (Moore *et al.*, 1978), partly due to the increased productivity and partly due to relatively tranquil bottom conditions that prevailed at this time. The early to early middle Eocene interval also shows highest diversities in the two major phytoplanktonic groups, i.e. calcareous nannoplankton (Haq, 1973), and dinoflagellates (Bujak, Williams, 1979). The peak diversity in the dependent zooplankton, such as the planktonic foraminifera, show a slight time-lag and occurred in the middle Eocene (Fischer, Arthur, 1977 ; see Fig. 8). With the exception of the dinoflagellates which show a second diversity peak in the late Eocene, plankton groups show a general decline in diversity in the remainder of the middle Eocene to late Eocene, and then a sharp decline in the early Oligocene.

As mentioned earlier, tropical and temperate flora and fauna migrated into the higher latitudes in response to this warming event. The occurrence of temperate floral elements as far as 60°N, led Wolfe (1978) to propose that the Milankovitch mechanism (change in the tilt of earth's rotational axis due to perturbations, precession and other phenomena) was responsible for the existence of the broad-leaved evergreens that require sufficient light throughout the year (i.e. lack of long dark winters) at these latitudes. Wolfe suggested that the lack of seasonality and low latitudinal temperature gradients would require a considerably smaller tilt-axis and hypothized that the tilt axis may have decreased gradually during the Paleocene to middle Eocene, from a value of about 10 to 5°, and then increased rapidly thereafter to 25-30° by the end of Eocene — with the resultant effects on global tectonics, climates and eventually the biosphere itself. Independent evidence for a large shift in the tilt of Earth's rotational axis, however, still has to documented for the Paleogene.

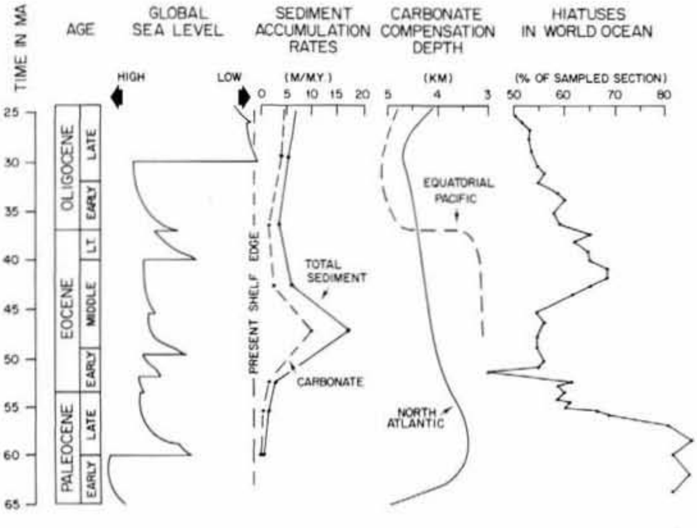


Figure 7

Paleogene sedimentalogical data plotted against global eustatic cycles recognized by Vail et al. *(1977). Sediment accumulation rates after Davies* et al. *(1977), fluctuations in the CCD after van Andel* et al. *(1975) and hiatuses in the world ocean after Moore* et al. *(1978).*

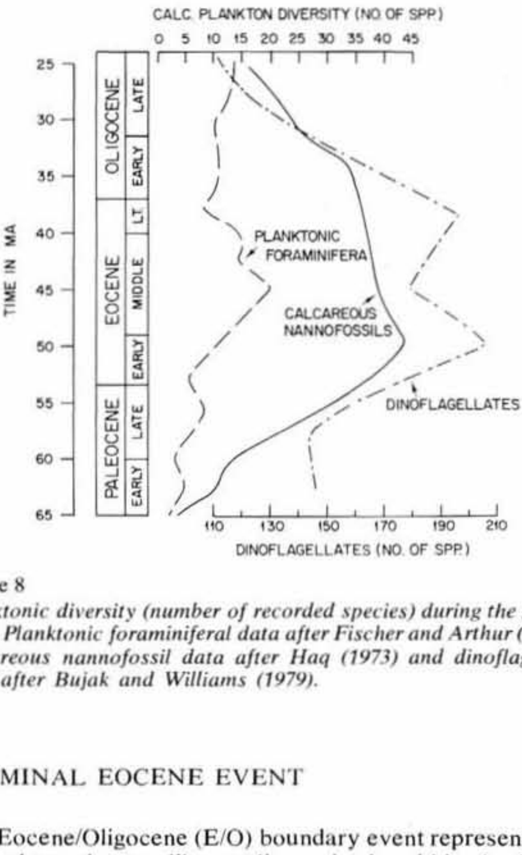


Figure 8

Planktonic diversity (number of recorded species) during the Paleogene. Planktonic foraminiferal data after Fischer and Arthur (1977), calcareous nannofossil data after Haq (1973) and dinoflagellate data after Bujak and Williams (1979).

TERMINAL EOCENE EVENT

The Eocene/Oligocene (E/O) boundary event represents the most dramatic step-like cooling episode within the larger cooling trend of the Cenozoic (Berger, 1979). This event caused wide-spread climatic deterioration, first documented in some detail by Savin *et al.* (1975) and Shackleton and Kennett (1975). A more detailed study across the boundary on Site 277 on Campbell Plateau in the southwest Pacific by Kennett and Shackleton (1976) documented a sharp drop in the isotopic paleotemperature in the earliest Oligocene (now considered to be closer to the E/O boundary). These authors suggested that the 4-5°C drop in bottom water temperatures, reflects the development of the psychrosphere as suggested earlier by Benson (1975). The sharp drop in the bottom and surface water temperatures at the E/O boundary have since been documented in numerous other oxygen-isotopic studies of marine sections in different oceans (see Fig. 6). However, there is still some question as to the timing of the development of the psychrospheric regime. Corliss's (1979) study of benthic foraminifera across the E/O boundary at Site 277 reveals a gradual change in the benthic assemblages in the latest Eocene, indicating in gradual development of the psychrosphere before the sharp drop in isotopic temperatures.

The terminal Eocene event was the antithesis of the early Eocene climatic optimum, with adverse effects on marine biota. The diversity of both the phyto- and zooplankton groups declined rapidly at this threshold (see Fig. 8).

Kennett and Shackleton (1976) proposed that the enrichment of benthic $\delta^{18}O$ represents the onset of cold bottom water activity that began when Tasman Sea opened enough to permit at least a partial thermal isolation of Antarctica and extensive cooling at sea-level that would have led to bottom water formation in significant quantities. The development of psychrospheric circulation is also held responsible for the occurrence of wide-spread early Oligocene hiatuses in the deep sea (Davies *et al.*, 1975, Moore *et al.*, 1978 ; see Fig. 7). The reduced corrosiveness of the new (more oxygenated) bottom water is thought to have led to the steep plunge of the CCD in the equatorial Pacific (Berger, 1973 ; van Andel *et al.*, 1975 ; see Fig. 7). The drop in CCD is also evident in the dramatic change in benthic fauna observed at DSDP Site 111 in the Labrador Sea, where predominantly agglutinated foraminiferal assemblages are abruptly replaced by calcareous benthic assemblages across the E/O boundary (Miller *et al.*, 1980).

Thierstein and Berger (1978) once again favour the isolation and reconnection of the Arctic to have caused the terminal Eocene event. They argue that a rapid spread of brackish water from the Arctic Ocean would disrupt the heat exchange between the deep and surface waters, reducing the moderating influence of the ocean on the global climate, and subsequently resulting in snow accumulation on Antarctica and formation of bottom water. In their model these authors suggested that the injection of lower salinity water would cause a global decrease in $\delta^{13}C$ values in benthic foraminifera. Although such a decrease has been recorded in some sections, it is not universal (see, e.g., Site 292 data from Benham Rise in the Philippines Sea in Keigwin, 1980).

Moreover, there is no evidence of a tectonically (or eustatically) caused isolation (and reconnection) of the Arctic Ocean at the end of the Eocene epoch. On the contrary, Gradstein and Srivastava (1980) show that middle to lower bathyal (1,000-2,000 m depth) conditions to have existed in the Baffin Bay, and an open connection from the North Atlantic to the Arctic, throughout the late Eocene and early Oligocene. The relatively minor regression near the E/O boundary documented by Vail *et al.* (1977) was not significant enough to have disrupted this connection.

EPILOGUE

As data from various different lines of investigations accumulates, the outlines of Mesozoic and Cenozoic paleoceanography is emerging — a brief account of the inferred Paleogene patterns and the more marked events during this interval has been presented above. It is obvious from this discussion that a number of important questions need to be resolved before more detailed paleoceanic reconstructions can be attempted with confidence. Foremost of these problems is a more accurate resolution of the timing of opening and closing of oceanic pathways. Prime questions that need immediate attention are :

1) a more accurate estimate of the timing of opening of the Norwegian-Greenland Sea and the establishment of the Arctic-Atlantic connection ;

2) the resolution of the plate tectonic history of the Arctic basin itself, beyond the resolution offered by the earlier studies (e.g. Herron *et al.*, 1974), especially the history of the passageways of the Arctic waters through alternative routes such as the Labrador Sea and the Bering Strait ;

3) a more accurate reconstruction of the history of subsidence (and periodic emergence ?) of the Greenland-Iceland-Faeroe Ridge, which is crucial to the understanding of the initiation of NADW and its important influence on the paleoceanography of the world ocean ;

4) the timing of the development of the shallow connection for surface currents, and subsequently the deep connection, at Drake Passage — estimates for the shallow connection vary from 38 Ma (Sclater, pers. comm.) to 30 Ma (Barker, Burrell, 1977). The initial development of a shallow connection must have led to an effective thermal isolation of Antarctica, and if the older estimate of this event is correct, the E/O boundary climatic decline must have been partly caused by this event ;

5) Vail *et al.*'s (1977) outline of eustatic cycles provides an important step forward in the study of paleoceans. It is becomming obvious that fluctuations in sea-level provide the primary forcing mechanism for oceanographic and climatic changes, rates of sediment supply to the oceans, and ultimately the biologic evolution. However, the magnitude and the timing of the transgressive and regressive events need better resolution if we are to use this information effectively in the unravelling the history of the paleoceans.

Most of these and other important questions require an interdisciplinary approach, and if the recent trend is any indication, the time seems ripe for greater cooperative effort, without which meaningful paleoceanographic reconstructions cannot be attempted.

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